## Keynote Address
## DESCANSO International Symposium

**21 September, 1999**

# The Critical Role of Communications and Navigation Technologies to the Success of Space Science Enterprise Missions

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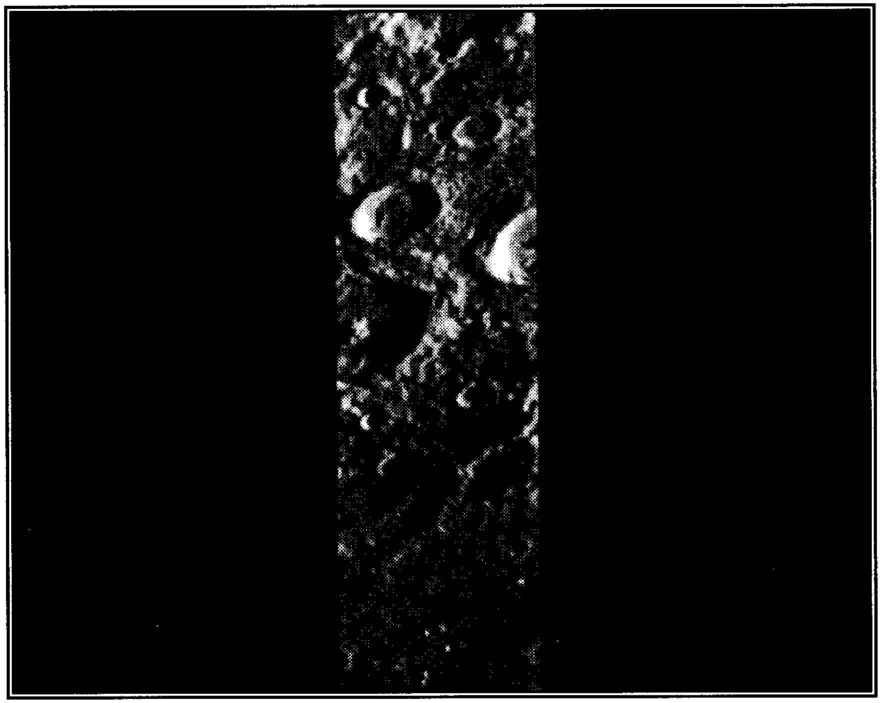
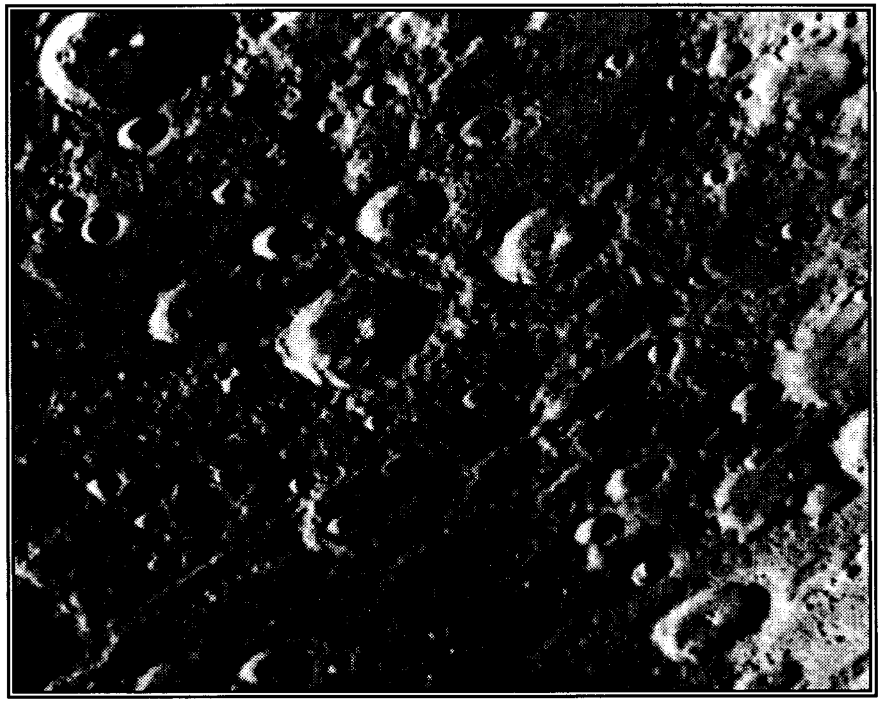
**Director, Space and Earth Science Programs**

# Unique Challenges of Deep Space Missions to Communications and Navigation

- Extreme Distance
  - Communications performance scales as $1/R^2$
  - Communicating with an Outer Planet mission to Neptune, Pluto is *~10 billion* times harder than with a commercial GEO satellite
- Long Round Trip Light Times
  - Onboard autonomy required in order to close decision loops faster than RTLT
  - Rapid response to in situ environments and conditions
- Wide Range of Environments
  - Challenging thermal, radiation, shock requirements
  - Fault-tolerant hardware and software
- Unique Navigation Scenarios
  - Small body ops, gravity assist trajectories, aerocapture/aerobraking, SEP, libration point missions, formation flying,
- High Launch Cost per Unit Payload Mass
  - Drives need for low mass, low power flight systems

# Benefits of S-band maser Ultra Cone for Mariner 10 (MVM '73)



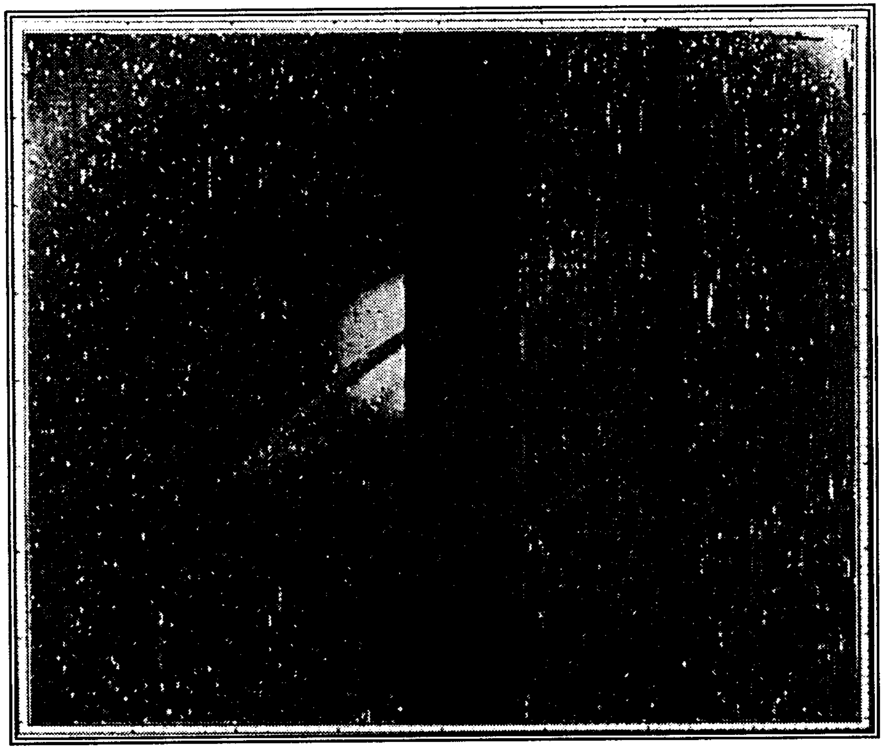


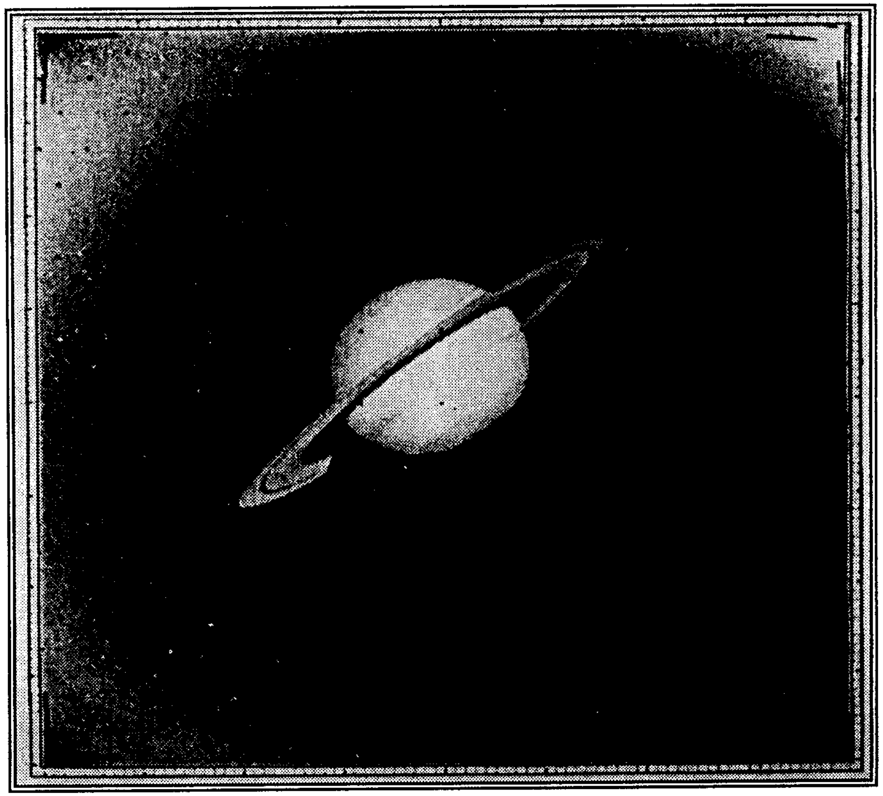
**Failure:** The spacecraft recorder failed,while MVM'73 enroute to Mercury, requiring realtime downlink data.

**DSN Advanced Systems response:** an S-band lower noise maser 'Ultra Cone' improved the link performance about 1 dB.

**Success:** Increased realtime downlink data rate from 22 to 117 kb/s for the Australian encounter.

# Enhancement of Voyager 1 at Saturn with X-band ground upgrades





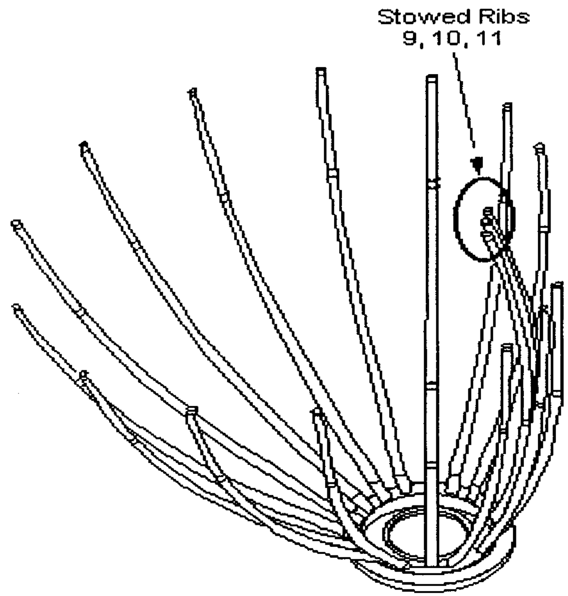
**Limitation:** During the Voyager 1 Saturn November 1980 close flyby, the downlink was limited to 29.9 kb/s data rate.

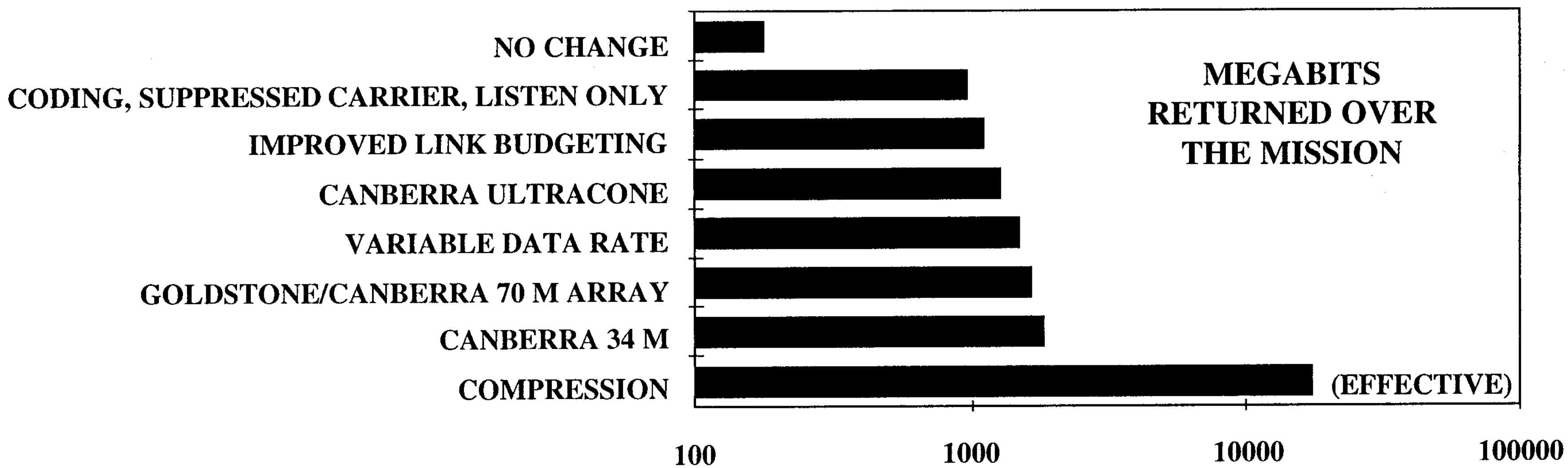
**DSN ground systems response:** Provide lower noise X-band masers, improved 64-m antenna efficiency, and array the 64-m with the 34-m 'standard' antennas.

**Enhancement:** 2 dB link improvement with 44.8 kb/s downlink, provided additional pictures of Saturn, including moons and ring detail, for important science enhancement.

# Recovery of Galileo with S-band upgrade

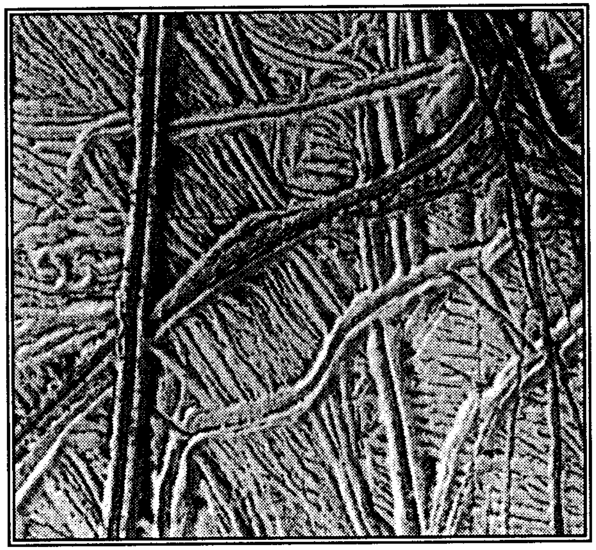
**Failure:** Galileo's X-band high gain antenna deployment failed April 1991, enroute to a Jupiter 1995 encounter, seriously compromising the downlink and planned data transfer.

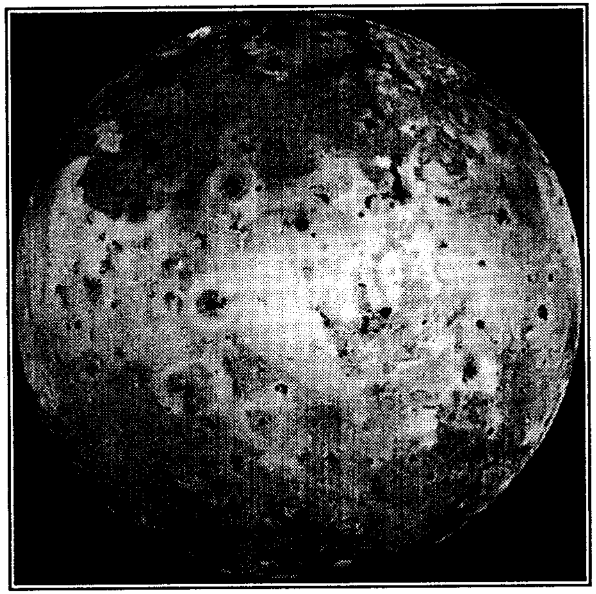



**Upgrades:** S-band upgrades provided for Galileo to meet 70% of the original planned science objectives

# Recovery of Galileo with S-band upgrade (cont.)

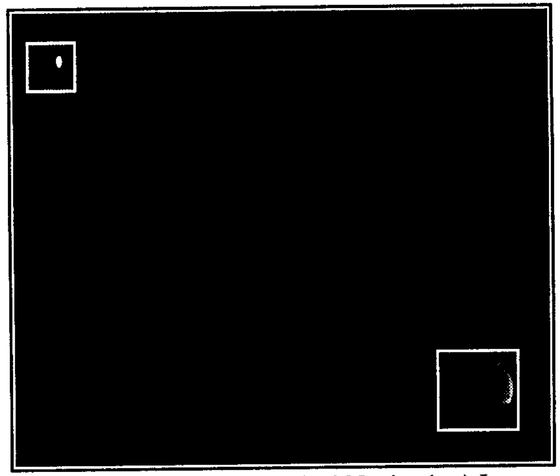




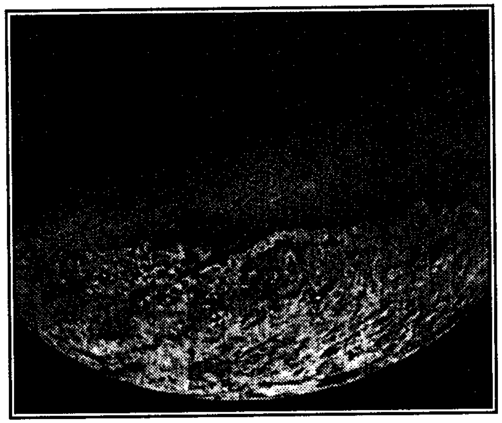
**Success:** Galileo met 70% of the original planned science objectives

# Benefit of Optical Navigation to Voyager Science

**By taking distant optical navigation images such as this on Voyager, orbit determination accuracies improved dramatically,**



Sample OPNAV (Optical Navigation) Image

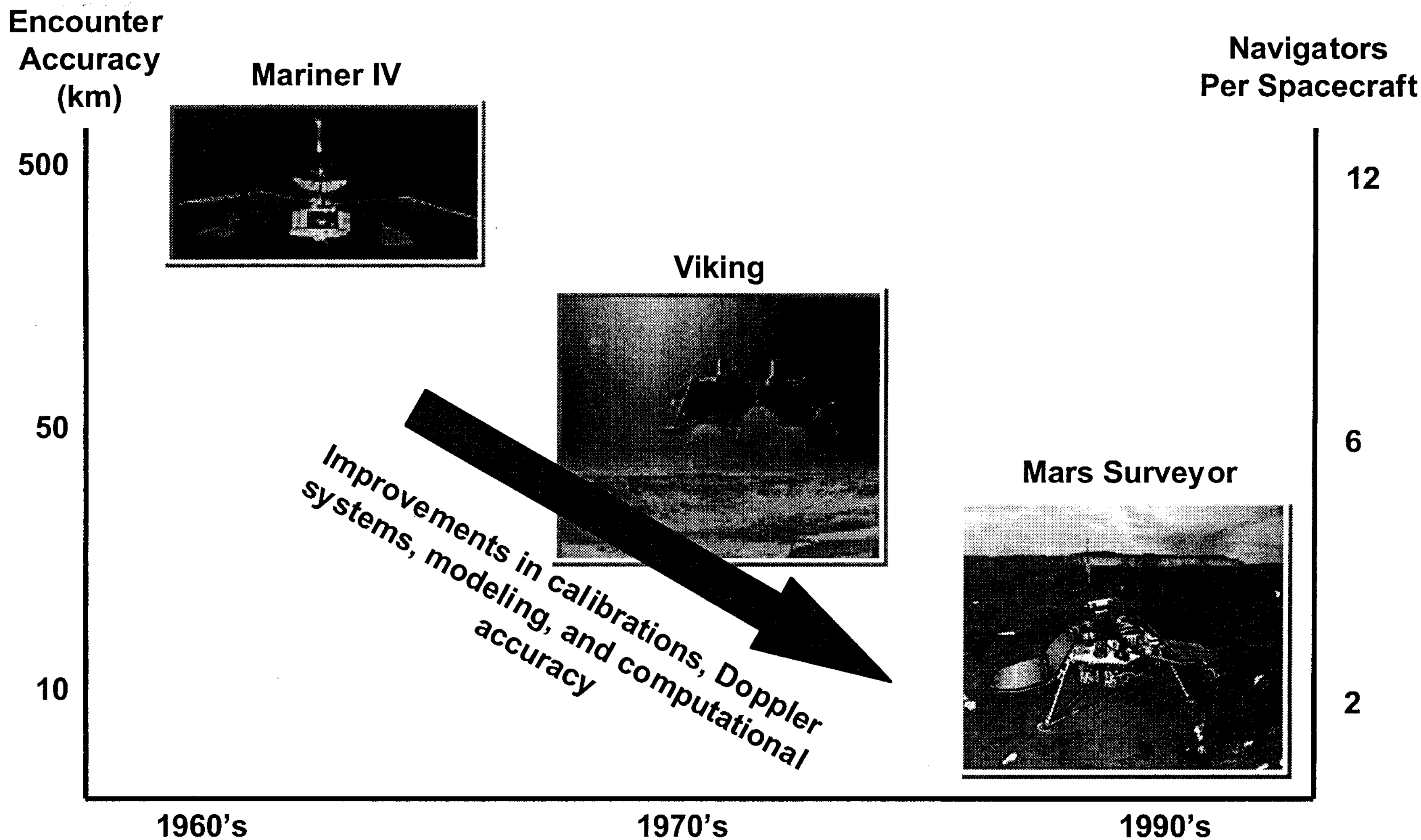


Triton Mosaic - Made possible in part by Optical Navigation

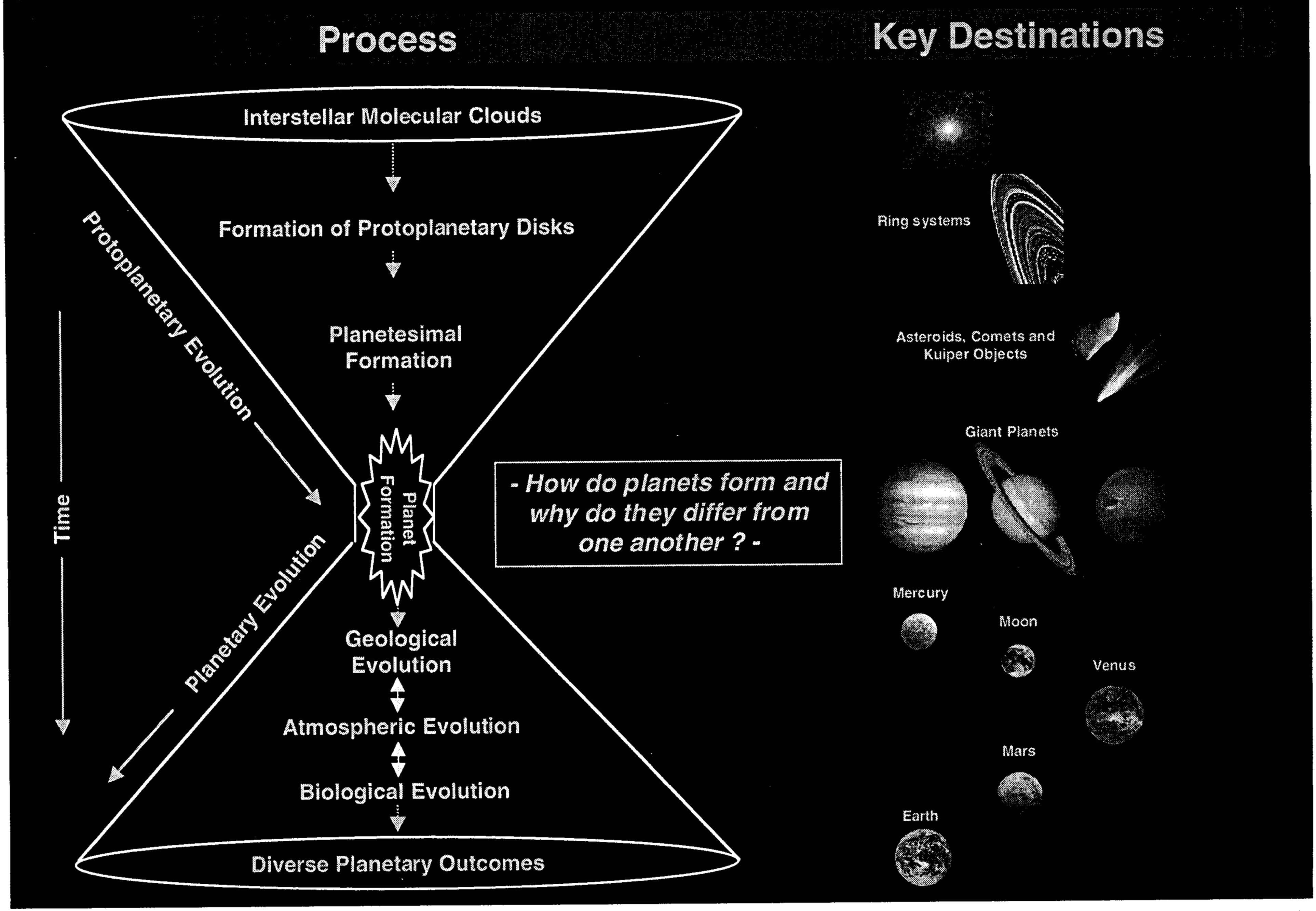
**allowing high-resolution science frames near satellite encounters such as this to become possible...**

**Without optical navigation, the Voyager mission would have returned only on the order of 10% of the high-resolution science that it did.**

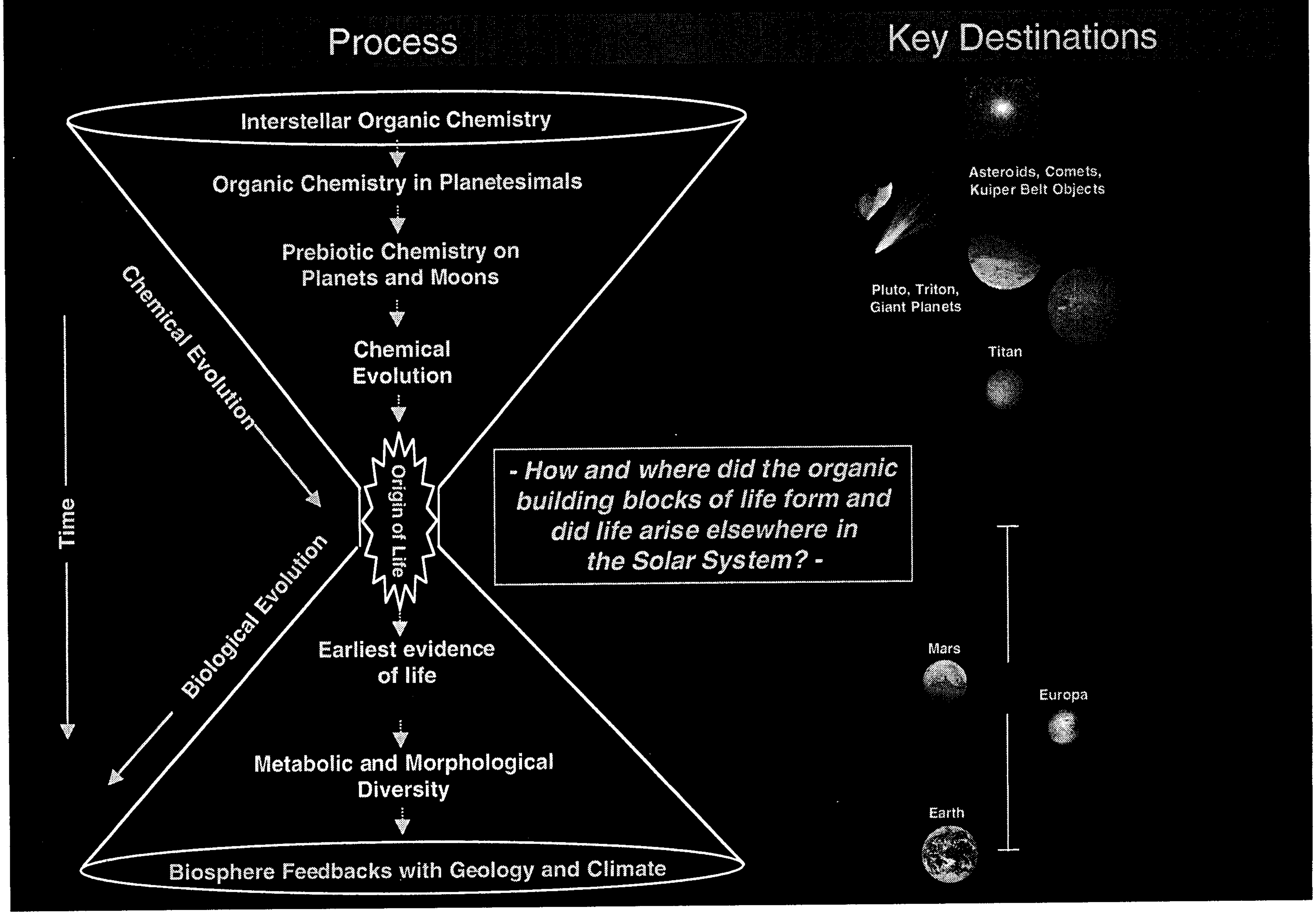
# Benefits of Improved Radio Navigation Accuracy to Mars Missions



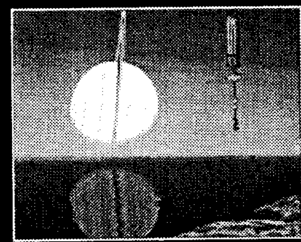
# Quest 1 - Explain the Formation and Evolution of the Solar System

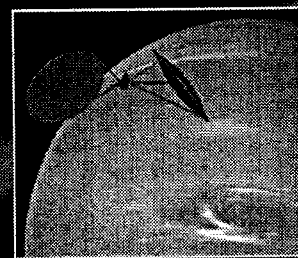


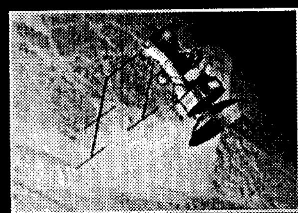
# Quest 2 - Seek the Origin of Life and its Existence Beyond Earth



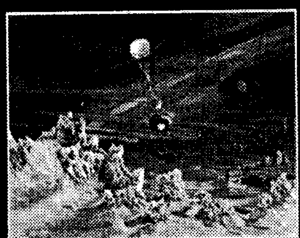
# Outer Planets Program: Exploring Organic-Rich Environments

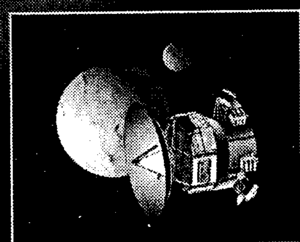

Titan Explorer

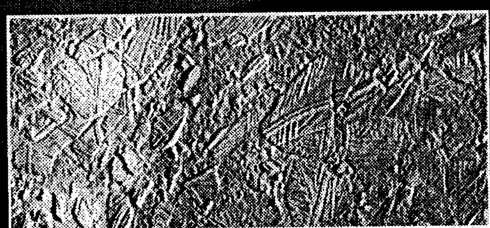

Neptune Orbiter

Europa Orbiter



Europa Lander

Cassini/Huygens



Pluto/Kuiper Express


Galileo-Europa

# Exploring Organic-Rich Environments: Europa Lander Mission

- *Critical Questions*
  - What is the age and composition of the Europa surface?
  - What organic chemical processes are taking place?
  - Is there any potential access to liquid water?
  - Are there any indications of biological activity?

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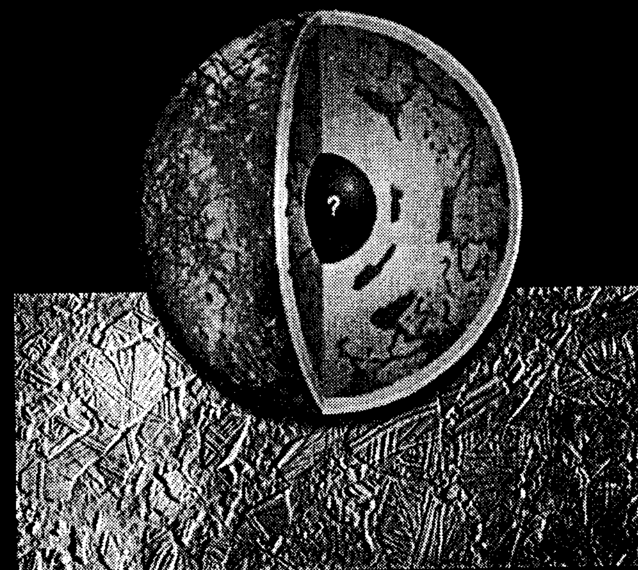
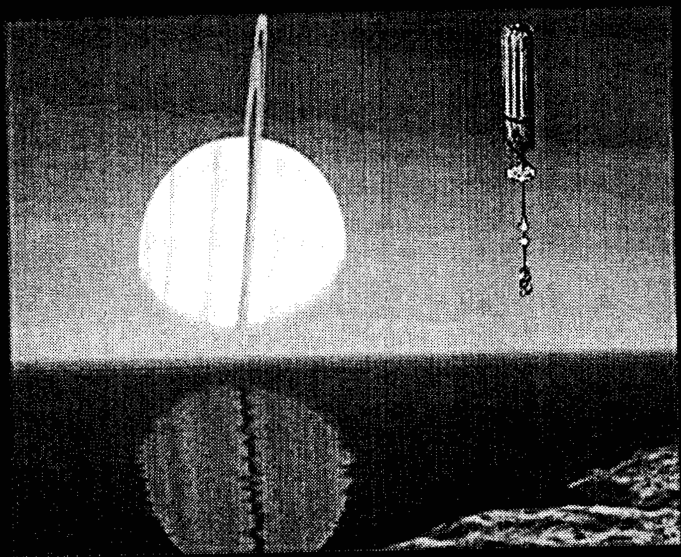
- Ready for mission start: 2005
- 6-8 year mission duration
- Technology demo of future subsurface access

- *Key Capabilities*
  - High performance, low mass propulsion for descent
  - Autonomous landing and hazard avoidance
  - Miniature organic chemistry laboratories
  - Sample acquisition & processing
  - Bioload reduction
  - Radiation tolerant components



# Exploring Organic-Rich Environments: Titan Explorer Mission



- *Critical Questions*
  - What prebiotic chemistry is taking place at Titan and what can it tell us about the primordial Earth…and the origin of life?
  - What is the composition of Titan's surface and how does it interact with the atmosphere?
  - How has Titan evolved over its history?

- Ready for mission start: 2006-2007
- Atmospheric and surface measurements
- Balloon or aircraft for mobility

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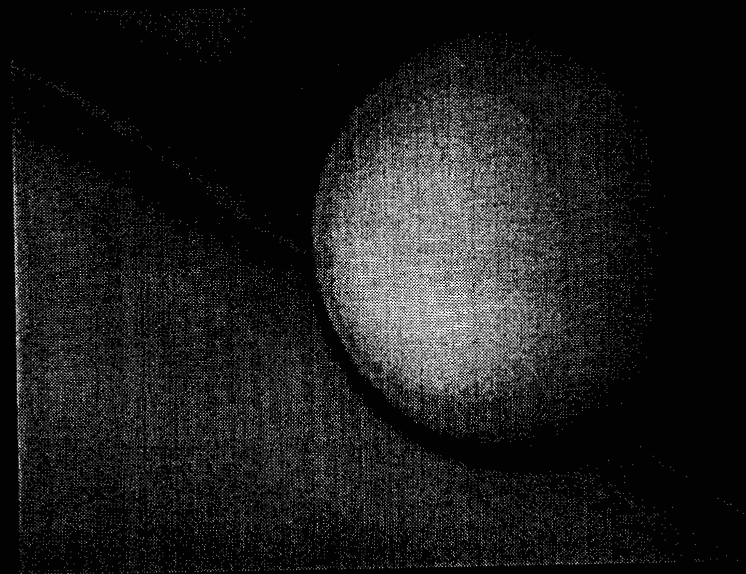
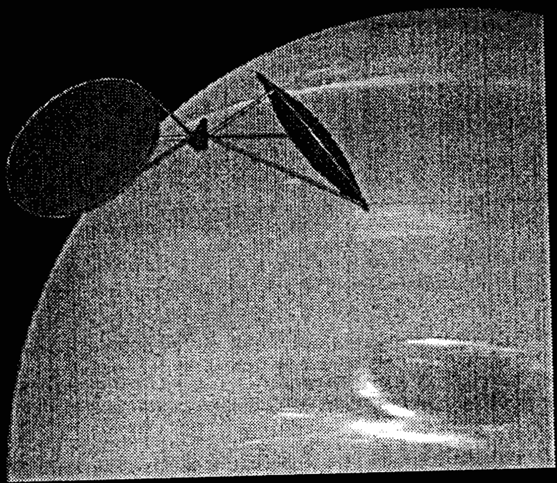
- *Key Capabilities*
  - Aerial platform or surface rover
  - Aerocapture at Titan
  - Miniature *in situ* chemistry lab
  - Sample acquisition
  - Bioload reduction



# Exploring Organic-Rich Environments: Neptune Orbiter Mission



- *Critical Questions*
  - What is Neptune's atmospheric structure and chemistry? What is the structure and behavior of its magnetosphere?
  - What are Triton's physical properties? Is it a captured Kuiper object? What can it tell us about the formation and evolution of the far outer solar system?
  - What are the dynamics of the rings and satellites?

- Ready for mission start: 2006-2007
- 10 year flight to Neptune, 2-4 year orbital tour
- Multiple flybys of Triton and
- sampling of upper atmosphere

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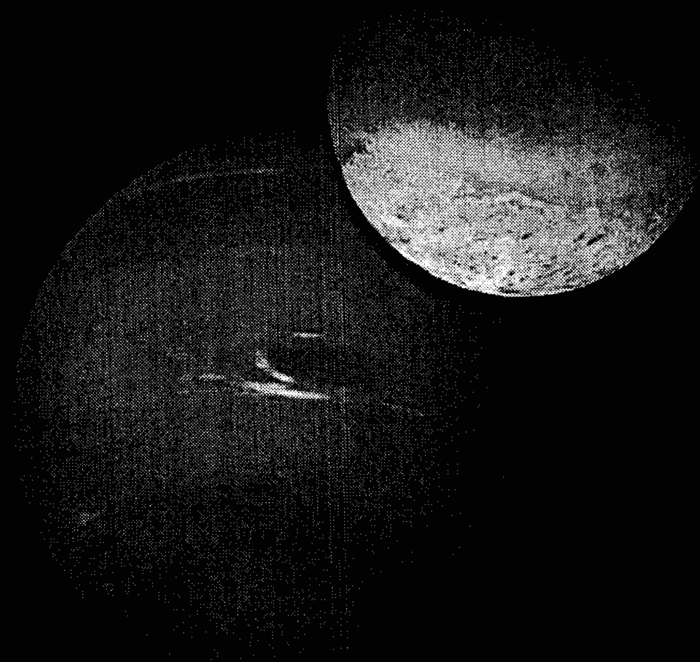
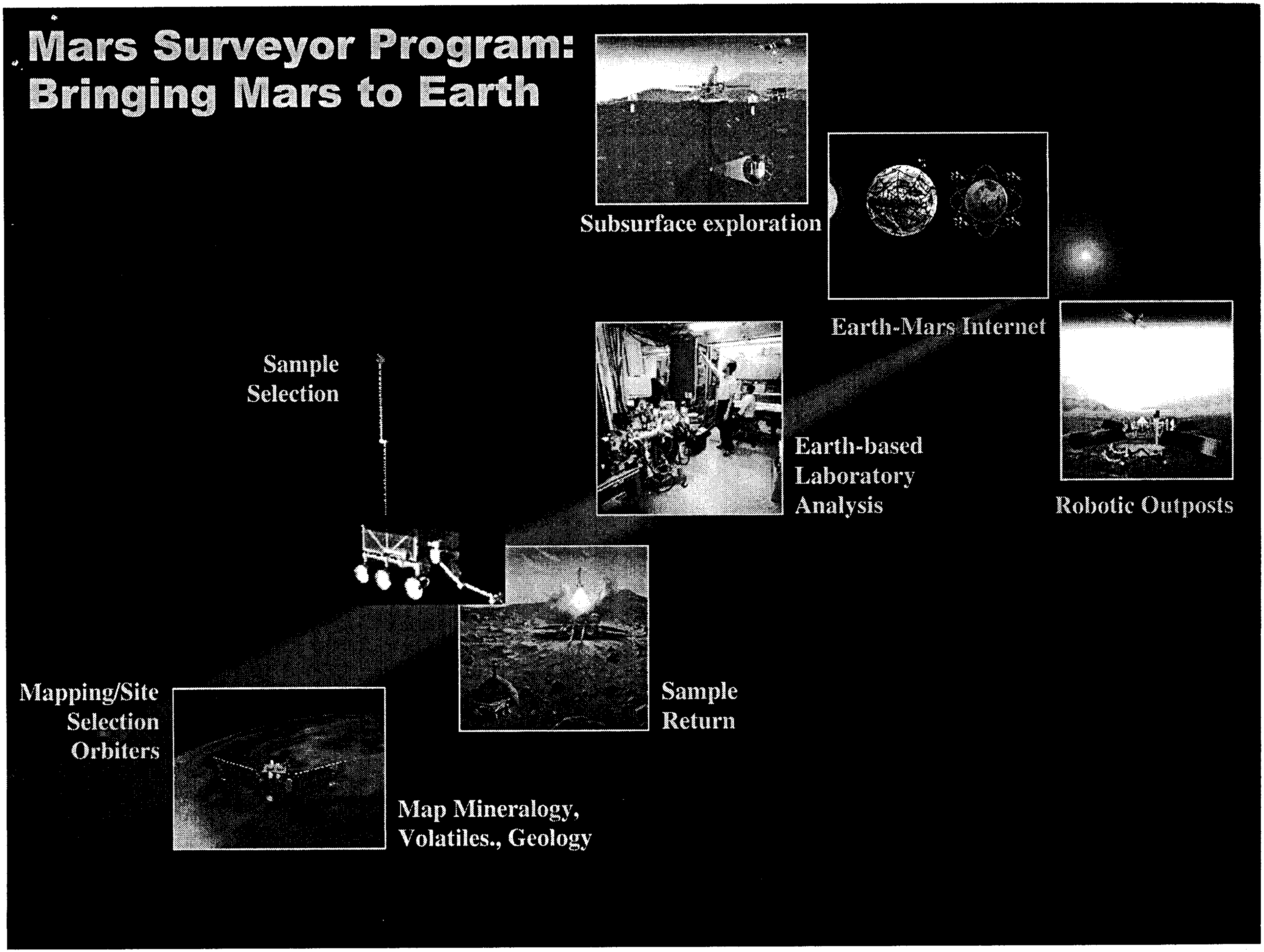
- *Key Capabilities*
  - Aerocapture
  - Advanced telecommunications system
  - High-power solar electric propulsion
  - Autonomous spacecraft operations
  - Temperature tolerant electronics

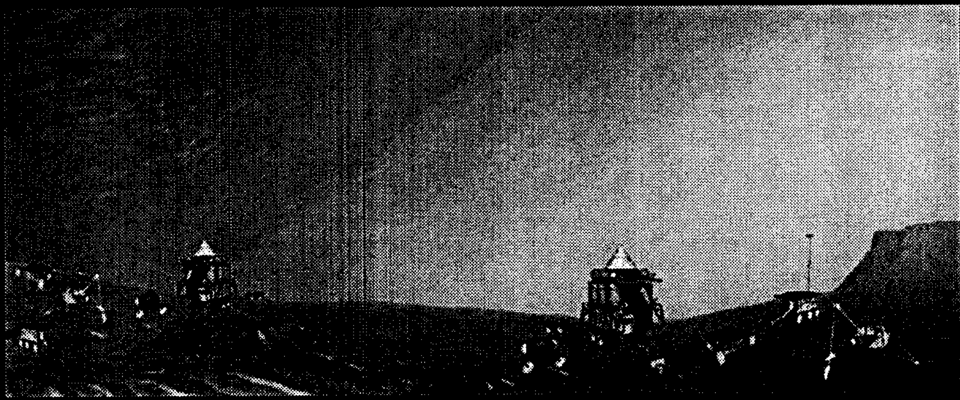



Mars Surveyor Program:
Bringing Mars to Earth
Subsurface exploration
Earth-Mars Internet
Sample
Selection
Earth-based
Laboratory
Analysis
Robotic Outposts
Mapping/Site
Selection
Orbiters
Sample
Return
Map Mineralogy,
Volatiles., Geology

# Robotic Outposts: Extending human senses into the solar system

*A new paradigm of exploration*

- Planet-scale *in situ* observations
- Investigation of complex sites
- Permanent, interactive, expandable, intelligent robotic outposts with remote human participation



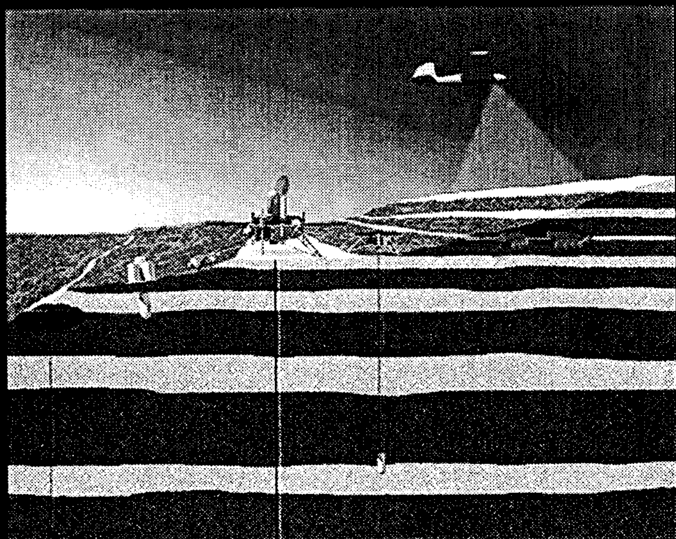
**Analogy to historical outposts: Permanent presence in a harsh environment, with resupply and communications with home base**

- **New capabilities required:**
  - Miniaturization of mobile vehicles
  - Autonomy and self-repair
  - Goal-directed automated task generation
  - Cooperative behavior of robotic vehicles
  - Remote human-robotic interfaces
  - *In situ* resource utilization

# Bringing Mars to Earth: Next Steps

## Mars Robotic Outposts

Near-term Mars Surveyor missions will identify high-priority scientific sites for further intensive exploration. Collections of cooperating multi-disciplinary exploration vehicles will collaborate in the exploration of such sites. These robotic outposts will also begin to emplace the infrastructure to be used by eventual human explorers.



**Mars Polar Terrain Science Laboratory**

Surface, subsurface, orbiting and airborne investigations

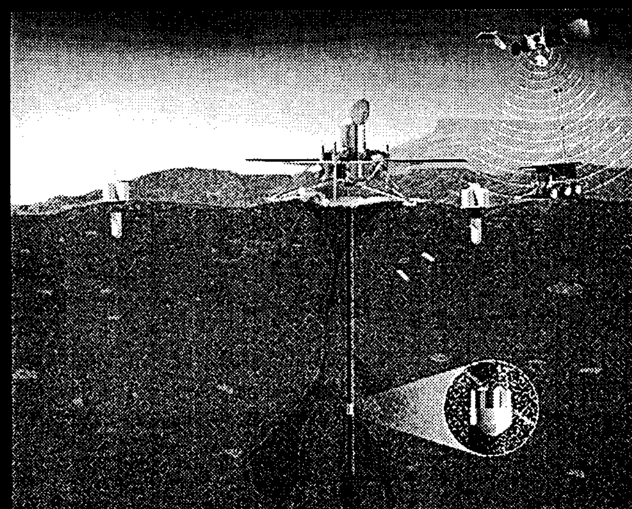
Central labs for analysis/coordination

Miniature ascent vehicles

### *Outpost Characteristics:*

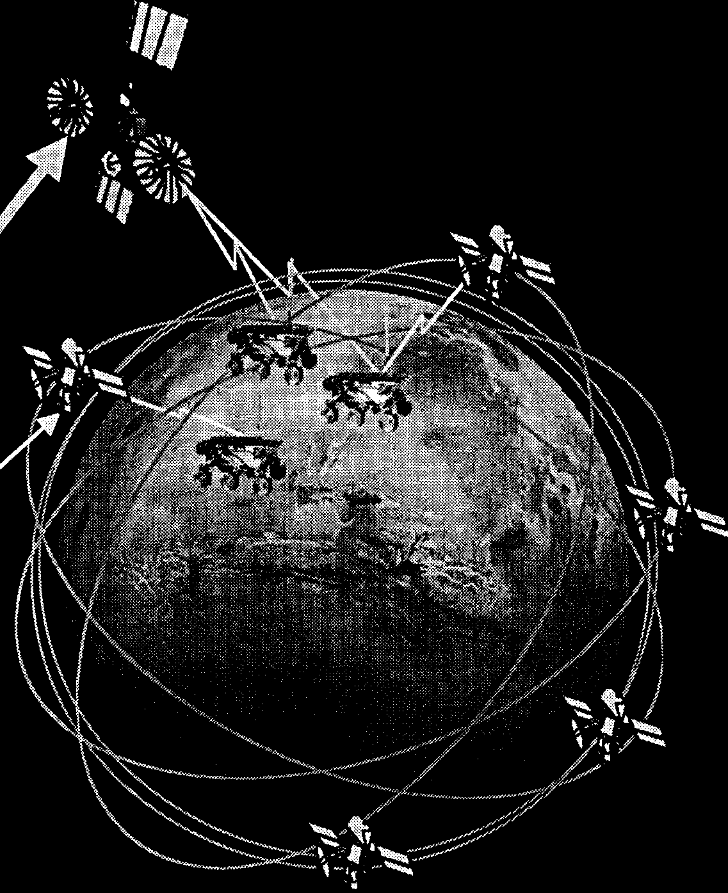
Distributed robots for wide-area, 3-D exploration and sampling

Ultra-miniature, extended life, expendable or replaceable, adaptable, interactive



**Hydrothermal Vent Science Stations**

# Mars Network



## *Low-Altitude ASAP Constellation*

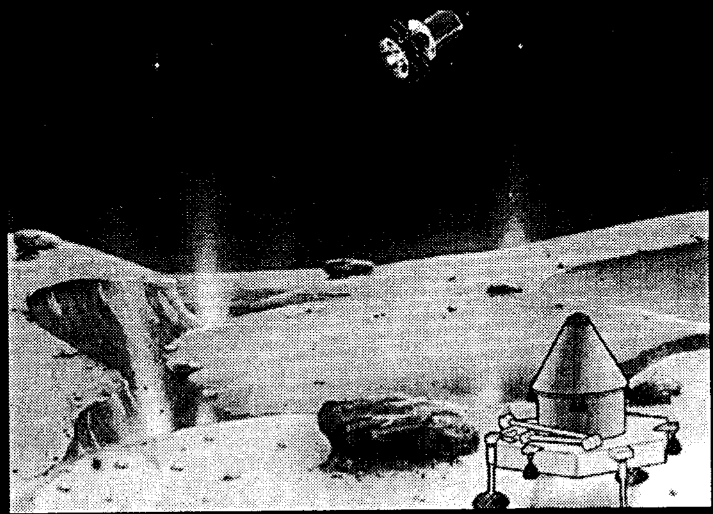
- *>1Gb/sol low-lat data return*
- *10-100m position determination*

## *Areostationary MARSAT*

- *1Mb/s near-continuous contact, streaming video*
- *100 Gb/sol data return*

- *Breakthrough communications bandwidth increases on interplanetary links*
- *Seamless end-to-end information flow across the solar system*
- *Layered architecture for evolvability and interoperability*
- *IP-like comm protocols tailored to operate over long round trip light times*
- *Efficient, miniature short-range communications systems*
- *Integrated communications and navigation services*

# To Build a Planet: Comet Nucleus Sample Return



- Ready for mission start: 2002-2003
- Mission duration 6 to 10 yrs
- Launch opportunities every year

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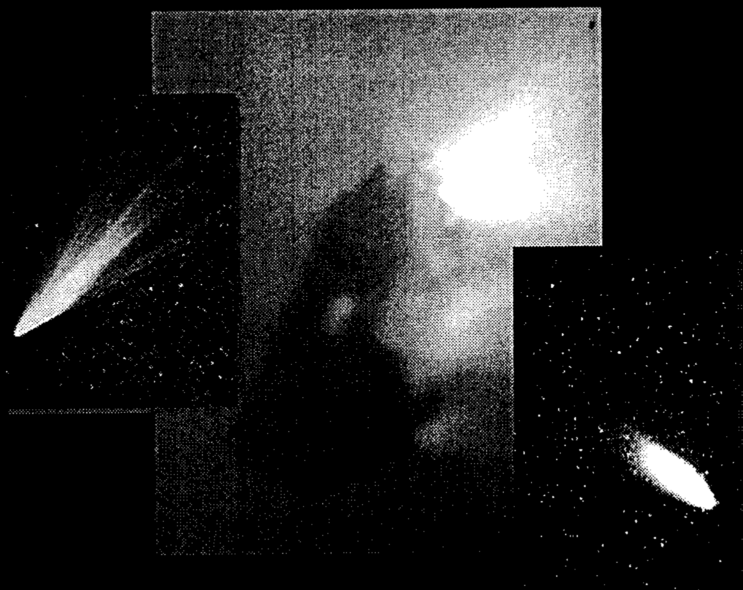
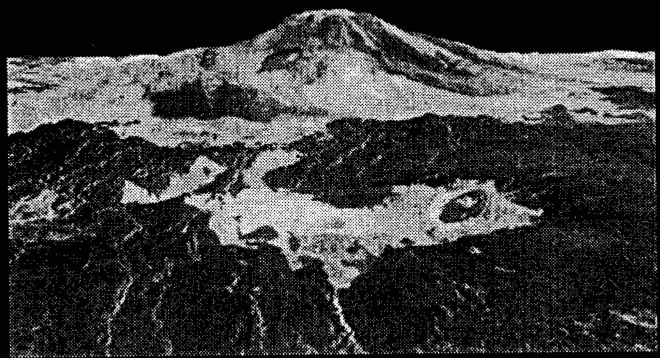
- *Key Capabilities*
  - Comet sample acquisition and handling
  - Improved solar electric propulsion
  - Autonomous control and navigation
  - High-efficiency solar arrays
  - Micro organic chemistry laboratory
  - High velocity Earth entry system

- *Critical Questions:*
  - What is the chemical composition of pristine comet nucleus material? What does it tell us about the primordial solar system?
  - How have comets evolved since their formation? How does their composition vary with depth and location on the nucleus?
  - What can we learn about the likely effects and mitigation of cometary impacts?



# To Build a Planet: Venus Surface Sample Return



- *Critical questions*
  - What is the age and chemical composition of Venus' surface? What is its atmospheric composition?
  - Why did Venus and Earth take such different evolutionary pathways?
  - Was there ever liquid water on Venus? Where did it go?
  - What can Venus tell us about the future of planet Earth?

- Ready for mission start: 2006-2007
- Short-duration surface stay time (~90 min)
- Balloon/rocket ascent
- Significant use of Mars Sample Return technologies

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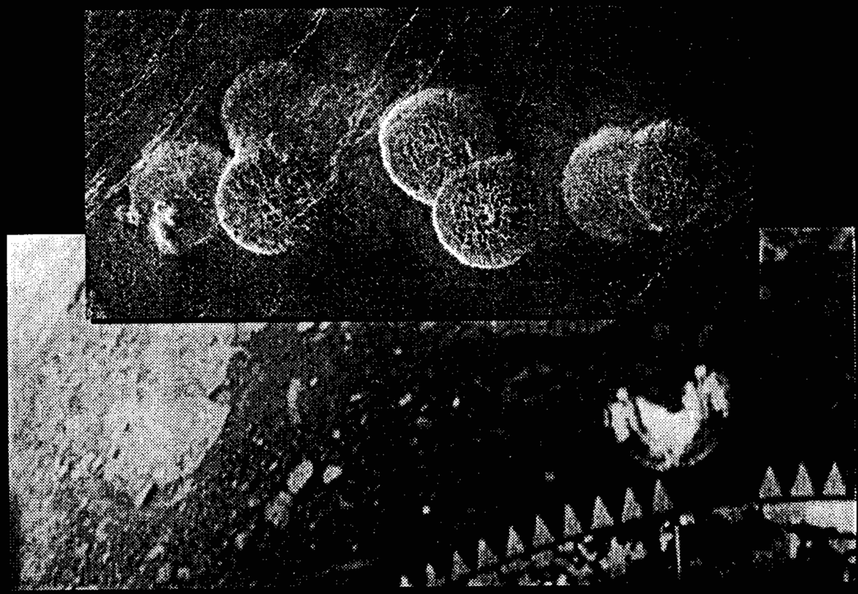
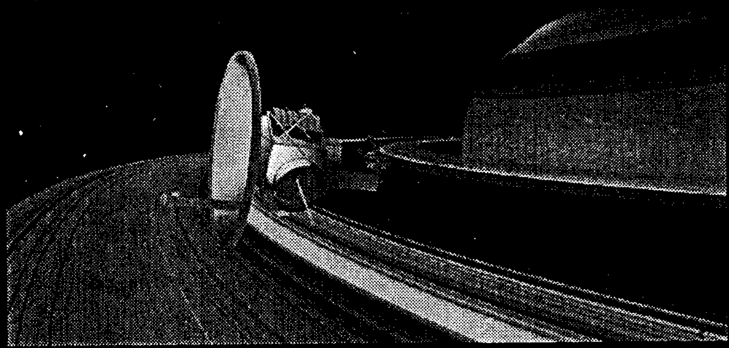
- *Key Capabilities*
  - Aerocapture
  - High temperature balloon system
  - Thermal control
  - Sampling mechanisms



# To Build a Planet: Saturn Ring Observer



- Ready for mission start: 2006-2007
- Aerocapture into close Saturn orbit
- Co-rotating, "hovering" orbit approx. 3 km above ring plane
- 30 days in close ring orbit

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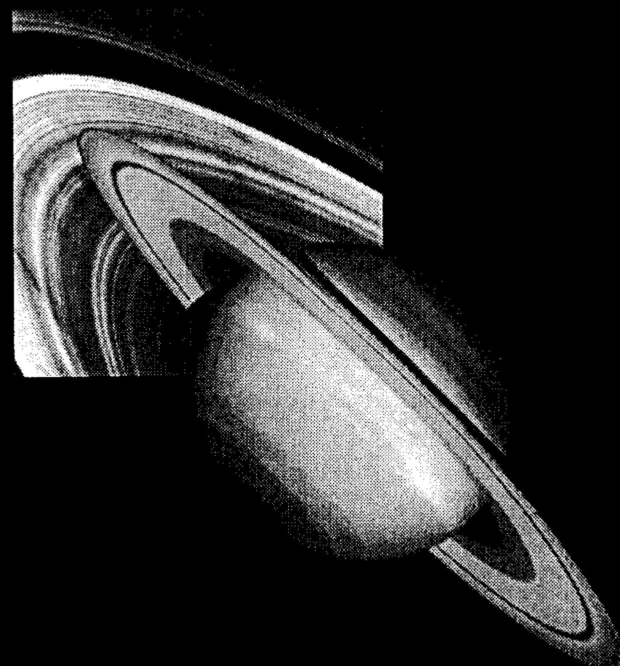
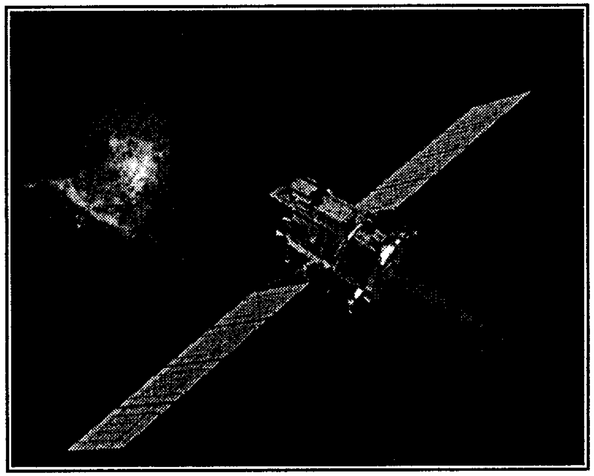
- *Critical Questions*
  - What are the physical properties of the icy particles comprising Saturn's rings?
  - What do their detailed, time-varying interactions tell us about the evolution of Saturn's rings?
  - What does the detailed study of Saturn's rings tell us about the early stages of planet formation and the present-day dynamics of extra-solar disks, accretion disks, and spiral galaxies?



- *Key Capabilities*
  - Aerocapture
  - Advanced propulsion: SEP or solar sail
  - Low mass, high-efficiency chemical propulsion
  - Autonomous navigation and maneuvers

# Optical Navigation - A Step Towards Navigation Autonomy

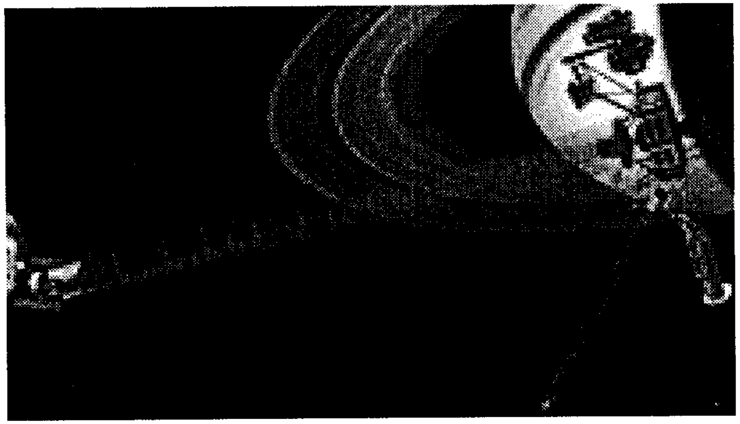


- **Deep Space-1 Cruise and Asteroid Flyby (August 1999)**
  - Navigated with an on-board autonomous optical system
  - During cruise, navigation accuracies of 300 km in position and 0.2 m/s in velocity were obtained
  - All approach maneuvers and solar-electric propulsion activities were performed based solely on optical data
  - Performed the closest flyby ever of an asteroid (27 km)

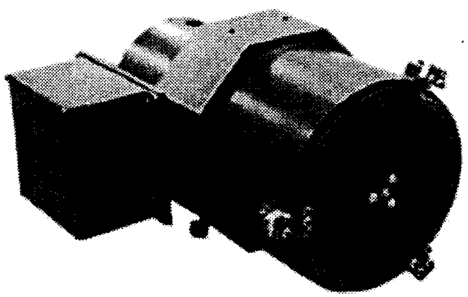
**Asteroid Braille 15 Minutes after DS-1 Encounter**

- **Benefits of Autonomous Optical Navigation**
  - Reduced cost to future missions from reduced navigation team size
  - Greatly reduced tracking requirements
  - Enhanced mission science by increased navigation accuracy at encounter, and improved science sequencing

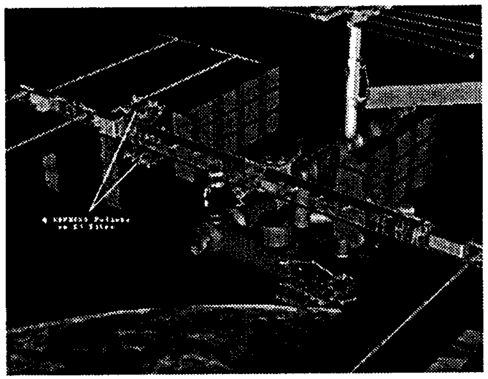
# Optical Communications



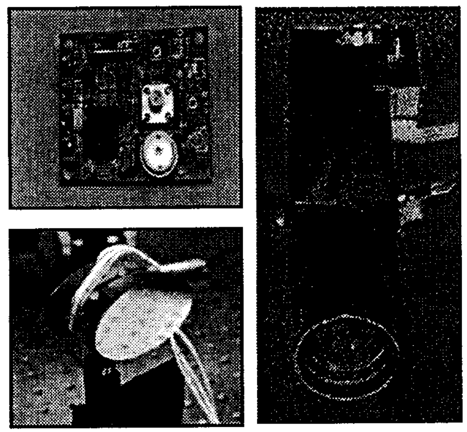
*Increased Data-Rate from a 10-cm Aperture Transmitter*



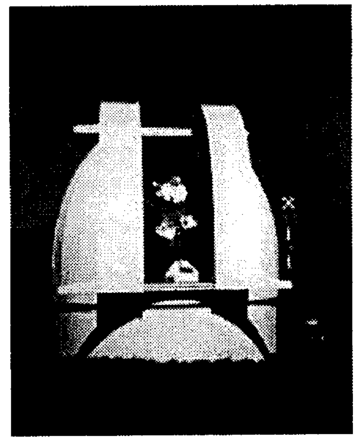
**Developed flight-like lasercomm terminal**



**Developing a 2.5 Gbps data-rate terminal for Downlink from Space-Station**



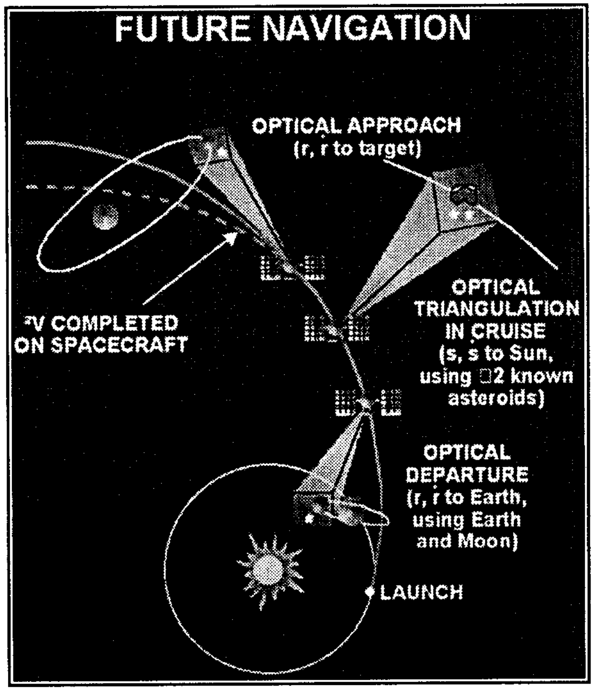
**Need to further develop acquisition/ tracking techniques & component efficiencies**



**Large aperture ground receiver development planned**

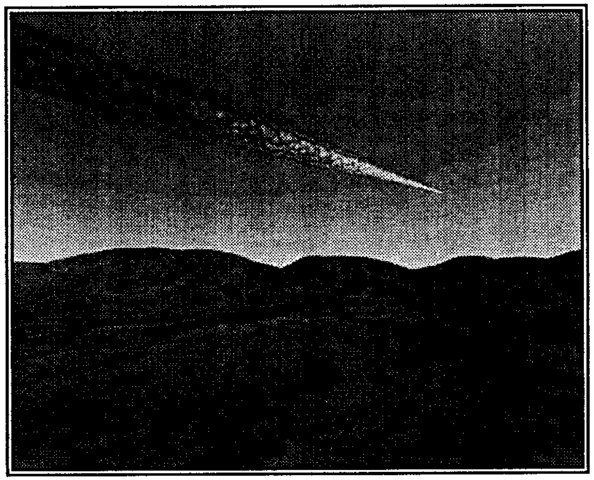
# Formation of a Spacecraft Constellation

# Key Navigation Technology Areas




**Autonomous Navigation**

**Interplanetary cruise, flybys, and orbiter scenarios for all missions**



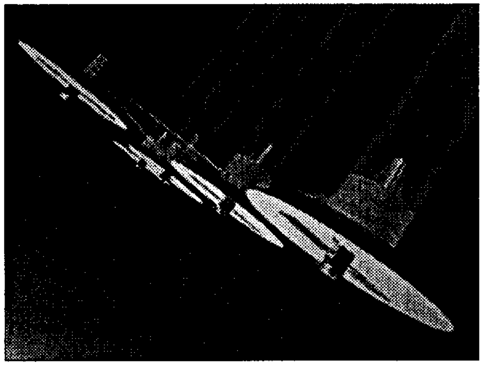
**Aerocapture**

**Missions going into orbit about Venus, Mars, Saturn, Uranus, Neptune**

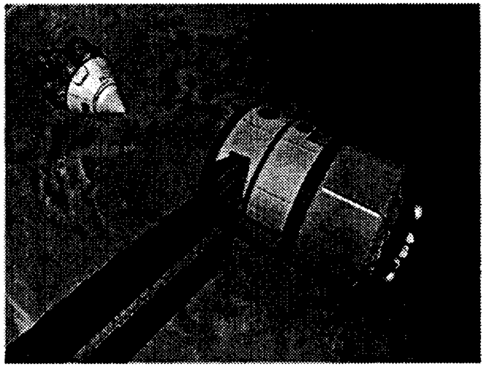
**Precision Landing**

**Landing on or hovering near small bodies, terrestrial bodies, or planetary satellites**

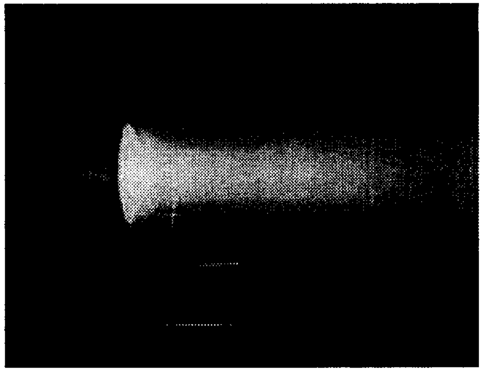
# Key Navigation Technology Areas (cont.)



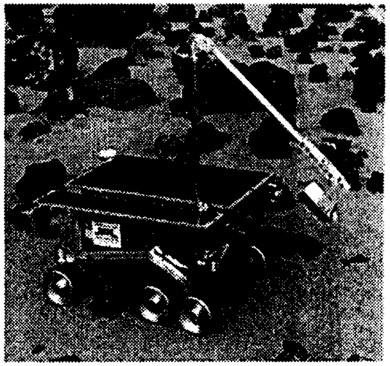
**Multi-Vehicle GN&C**
**Mars constellations, formation flying, etc.**



**Rendezvous & Docking**
**Sample return missions to terrestrial planets, small bodies, and planetary satellites**



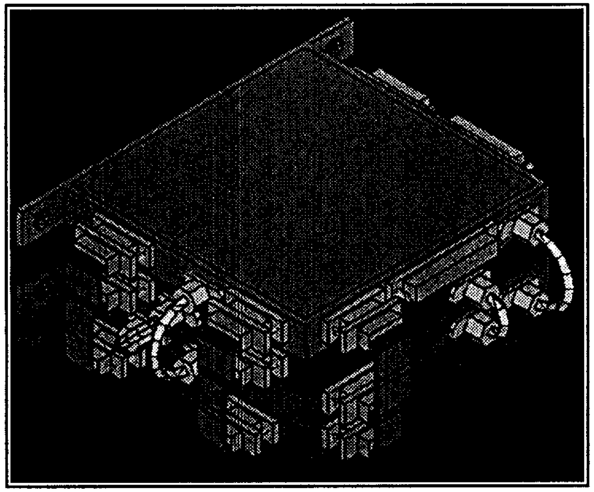
**Low-thrust Guidance & Navigation**
**Mercury, small body and outer planet missions**



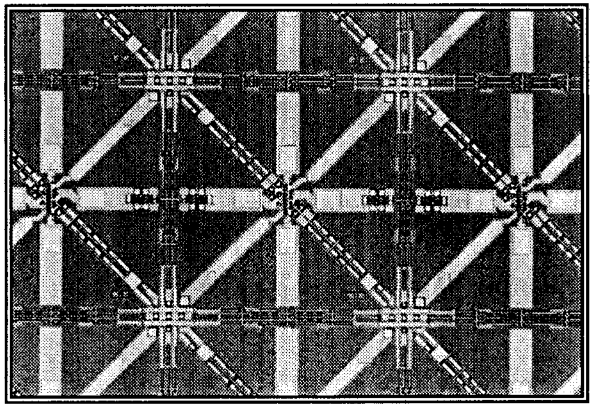
***In-Situ* Vehicle GN&C**
**Rovers, balloons, submarines, and aircraft, on planets, satellites, and small bodies**

# Ka-Band Communication Technology

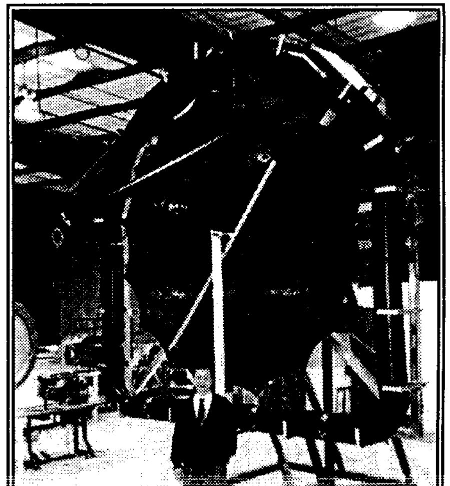
*Ka-band opens up new trade-space for future mission designs: higher data return or smaller S/C antenna, reduced mission contact time...*



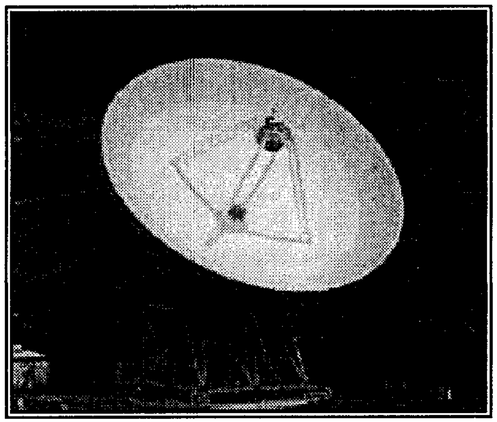
Spacecraft Transponding Modem
•High performance in a small space



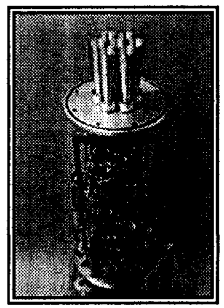
Quasi-Optic GaAs Amplifiers
•Efficient Ka-band amplifiers



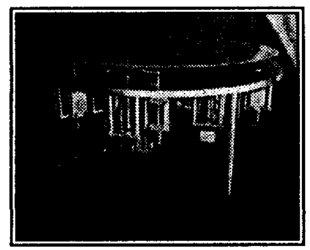
Inflatable Ka-band Antenna
•Lightweight & deployable



DSN Ground Antennas include Ka-band:
•Cryogenic Low noise amplifiers
•Combined X/X/Ka band antenna feeds
•Ka-band Transmitters
•Compensation of gravitational distortion effects of antenna surface and structure at Ka-band (via array feed and deformable mirror techniques)

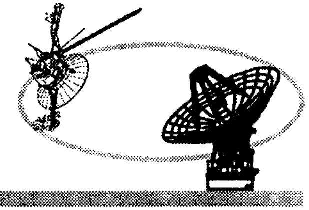


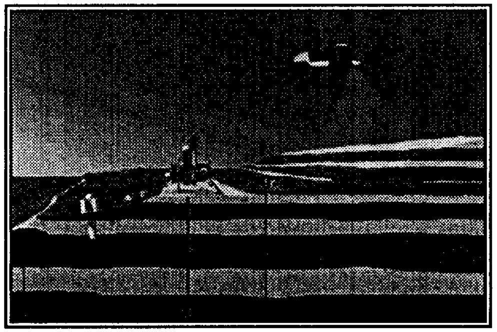
Array Feed

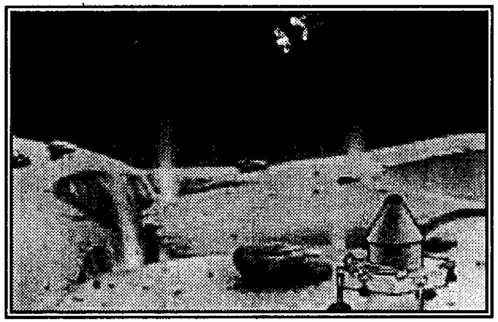


DeformableMirror

# In-Situ Communications Technologies







<u>Heterogeneous Networks of Science Elements and Spacecraft</u>

Versatile, reconfigurable, radios, ultra low mass / power radios integrated with science sensors, reliable network architectures and efficient protocols

For Robotic Outposts on Mars, and possibly Europa, for Sensor Webs

<u>In-Situ Science and Sample Return Missions</u>

Compact, self contained, multi-mission radios with greatest functionality at lowest mass and power.

For Formation Flying Spacecraft and Sample Return Missions such as at comets or planets where no comm. infrastructure exists

<u>Radios for Harsh Environments</u>

Micro-transceivers and antennas designed for very cold, very hot, high radiation, or unusual comm channel, environments. New component technologies required and detailed understanding of performance vs. environment trades.

For deep in-situ sampling to many planetary and small bodies such as Europa, Titan, comets ...